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Experiments and Analysis of Data on Shear Wave Propagation in Shallow Water Sediments

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Introduction

Research conducted under this contract was part of the Shallow Water Acoustics ARI. The long-range scientific objectives of the ARI were to determine the physical parameters that control acoustic propagation in shallow water and their relationship to geological structure and processes in order to improve acoustic monitoring capability. Specific objectives of this contract were to develop instrumentation, field procedures, and data inversion methods required for efficient high resolution determination of elastic parameters of bottom sediments as functions of depth and location, and to evaluate effects of lateral heterogeneity and anisotropy. This research was conducted in close cooperation with John I. Ewing and others at Woods Hole Oceanographic Institution.

Bottom mounted sources and receiving arrays were developed to effectively produce and record both longitudinal (P/SV, Rayleigh, Stoneley/Scholte) wave and transverse (SH, Love) wave reflection/refraction data. The shear generating sources used are designed to produce horizontally polarized (port and starboard) as well as longitudinal energy; summed port-starboard pairs emphasize longitudinal energy; differenced pairs emphasize transverse energy. A thirty element digital accelerometer/hydrophone array also was developed and used during the course of this contract. The elements of the array have one meter spacing; each consisting of three orthogonal accelerometers (flat from 2 to 500 Hz), a hydrophone and a vertical direction sensor. Each of the 4 components recorded produces unique data that provide additional information on wave type, velocity/attenuation structure, scattering, lateral heterogeneity, anisotropy, and instrument-bottom coupling (possible signal distortion). During two, two-week field experiments (in 1986 and 1988) shear velocities were obtained for the uppermost sediments in shallow water off New Jersey and Martha's Vineyard. The data exhibit strong evidence of anisotropy and lateral heterogeneity in shear velocity of the uppermost sediments at a number of locations. The data have been inverted to velocity/attenuation-depth sections with the aid of synthetic seismograms and other analytical techniques.

This research has demonstrated that high resolution longitudinal and transverse mode shear data can be obtained in shallow water regions and inverted to obtain shear velocity/attenuation vs. depth models.

Following is a list of reports and publications resulting from this research. Appendix A is a preprint of a paper in press in the Proceedings of the 38th Navy Symposium on Underwater Acoustics; Appendix B is the summary of a paper submitted to Geophysical Journal International; Appendix C is the abstract of a paper near completion for submission to Journal of Geophysical Research. A - summarizes the instrumentation developed and field procedures and shows examples of data analysis; B - emphasizes analysis for anisotropy; and C - provides a complete description of the data analysis and geophysical and geological interpretation. An additional paper on the instrumentation is being prepared for submission to Marine Geophysical Researches.

Reports and Publications Resulting From This Research

Berge, P. A., S. Mallick, and G. J. Fryer, "Reflectivity modeling of transverse isotropy in shallow water marine sediments," *AGU abstr., EOS*, vol. 69, p. 1329, 1988.

Berge, P. A., S. Mallick, G. J. Fryer, N. Barstow, J. A. Carter, G. H. Sutton, and J. I. Ewing, "In situ measurement of transverse isotropy in shallow-water marine sediments," *Geophys. J. International*, submitted, 1990.

Carter, J. A., G. H. Sutton, N. Barstow, and J. I. Ewing, "Synthetic modeling of shear waves in shallow marine sediments," *J. Acoust. Soc. Am.*, vol. 82, p. S112, 1987.

Carter, J. A., J. I. Ewing, G. H. Sutton, and N. Barstow, "Shallow water sediment properties derived from high frequency shear and interface waves," *J. Geophys. Res.*, in preparation for submission, 1990.

Ewing, J. I., G. H. Sutton, G. M. Purdy, and D. L. DuBois, "Studies of geoacoustic properties of shallow water sediments," *AGU abstr., EOS*, vol. 68, p. 354, 1987.

Harris, D. and G. H. Sutton, "Soft sediment shear wave sensor string," *AGU abstr., EOS*, vol. 69, p. 1319, 1988.

Sutton, G. H., J. I. Ewing, N. Barstow, and J. A. Carter, "Measurement of horizontally polarized shear waves in shallow marine sediments," *AGU abstr., EOS*, vol. 67, p. 1083, 1986.

Sutton, G. H., J. I. Ewing, D. L. DuBois, N. Barstow, and J. A. Carter, "Shear velocity/attenuation models for shallow marine sediments: offshore New Jersey," *AGU abstr., EOS*, vol. 68, p. 354, 1987.

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Sutton, G. H., N. Barstow, J. A. Carter, J. I. Ewing, and D. Harris, "High-resolution profiling of shallow water sediment shear velocity," *Seism. Res. Let.*, vol. 60, p. 16, 1989.

Sutton, G. H., J. A. Carter, and N. Barstow, "Shear velocity anisotropy and lateral heterogeneity in shallow-water marine sediments," *Shear Wave Workshop*, September 13, 1989 at Woods Hole Oceanographic Institution, 1989.

Sutton, G. H., N. Barstow, J. A. Carter, and J. I. Ewing, "Experiments and analysis of data on shear wave propagation in shallow water sediments," *Navy Symposium on Underwater Acoustics*, November 14-16, 1989, Biloxi, MS (32 p.), in press, 1990.

Sutton, G. H., D. Harris, and J. I. Ewing, "A three-component accelerometer/hydrophone receiving array and sources for shear waves (SH and SV) in shallow water marine sediments," *Mar. Geophys. Res.*, in preparation for submission, 1990.

Appendix A
(In press in Proceedings of the 38th Navy Symposium on Underwater Acoustics)

Experiments and Analysis of Data on Shear Wave Propagation in Shallow Water Sediments

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Abstract

Modern models of acoustic propagation in coastal regions have demonstrated clearly the need for knowledge of the sub-bottom shear velocity and absorption, as functions of depth, to adequately predict the propagation loss. Bottom mounted sources and receiving arrays are used to effectively produce and record both longitudinal (P/SV, Rayleigh, Stoneley/Scholte) wave and transverse (SH, Love) wave reflection/refraction data. The shear generating sources used are designed to produce horizontally polarized (port and starboard) as well as longitudinal energy; summed port-starboard pairs emphasize longitudinal energy; differenced pairs emphasize transverse energy. A newly develcped thirty element digital accelerometer/hydrophone array is used to study seismo-acoustic propagation in shallow water. The elements of the array have one meter spacing; each consisting of three orthogonal accelerometers (flat from 2 to 500 Hz), a hydrophone and a vertical direction sensor. Each of the 4 components recorded produces unique data that provide additional information on wave type, velocity/attenuation structure, scattering, lateral heterogeneity, anisotropy, and instrument-bottom coupling (possible signal distortion). Shear velocities are obtained for the uppermost sediments in shallow water off New Jersey and Martha's Vineyard. The data exhibit strong evidence of anisotropy and lateral heterogeneity in shear velocity of the uppermost sediments at a number of locations. The data are inverted to velocity/attenuation-depth sections with the aid of synthetic seismograms and other analytical techniques.

I. INTRODUCTION

In this paper we describe instrumentation and techniques that have been developed and implemented during an ONR Accelerated Research Initiative in Shallow Water Acoustics to generate, record, and interpret both horizontally and vertically polarized shear waves in shallow water sediments. Results provide information on shear-wave velocity-depth relationships, attenuation, anisotropy, and lateral refraction.

Modern models of acoustic propagation in coastal regions have demonstrated clearly the need for knowledge of the sub-bottom shear velocity and absorption, as functions of depth, to adequately predict the propagation loss (Akal, 1980; Ferla *et al.*, 1989; McDaniel and Beebe, 1980; Vidmar and Koch, 1986; Beebe and Holland, 1986). These authors note the importance of bottom rigidity as a low frequency loss mechanism in model/data comparisons and the general lack of adequate shear wave environmental data. Akal (1980) illustrates the increasing importance of sea-floor dependent propagation losses at lower frequencies and the existence of an optimum (minimum loss) frequency resulting from the interaction of the different major loss mechanisms. The optimum frequency is dependent upon water depth and upon sea floor geoacoustic characteristics. A range of optimum frequencies from about 50 to 800 Hz is shown for sediment ranging from clay to course sand; greater water depth shows generally lower frequencies for all sediment types.

The shear velocity of unconsolidated and semi-consolidated sediments is less than that of sound in water and ranges down to a few 10's of meters/sec for high porosity sediments. This makes 'total' reflection of a hydroacoustic wave impossible and some energy generally will be converted to shear in the bottom. The conversion efficiency depends upon angle and impedance contrast. Vidmar, 1980, investigated the dependence of bottom reflection loss on the geoacoustic parameters of solid sediments and found: shear and compressional velocities in both the sediments and substrate are clearly

important parameters; sediment shear and compressional gradients are also important; shear and compressional attenuations are important at certain frequencies and layer thicknesses. Stern, *et al.*, 1983, have extended this work utilizing the Biot, 1962, (Stoll, 1980) model for dissipative, water-saturated sediments. Earlier, Hawker, 1979, demonstrated the importance of conversion to Stoneley (Scholte) interface waves, whose properties depend strongly on sub-bottom shear velocities, as a loss mechanism in plane wave reflection problems. Hamilton (1976a and b, 1979) has compiled the most complete summaries of existing data on shear velocities, V_p-V_s ratios (Poisson's ratios), and shear attenuation in marine sediments and rocks. These data are included in his geoacoustic models of the sea floor (Hamilton, 1980). Milholland *et al.*, 1980, produced geoacoustic models for deep-sea carbonate sediments based on ultrasonic measurements on JOIDES cores, that include shear velocity and shear anisotropy versus depth.

Very little *in-situ* data exist on shear velocity and attenuation in ocean bottom sediment. Almost all of that data is derived from interpretation of low frequency Stoneley/Scholte interface waves, generally less than 100 Hz (Davies, 1965; Essen, 1980; Rauch, 1980, 1986; Schirmer, 1980; Schmalfeldt, 1986; Snoek *et al.*, 1986; Jensen and Schmidt, 1986). These waves involve both compressional and shear energy, and fall off exponentially with distance above and below the bottom. They are dispersive if the velocities change away from the interface and can be considered to be a particular solution of the general Rayleigh wave problem. The experimental procedure generally involves firing explosive charges near the bottom and recording on bottom geophones (or hydrophones) at different ranges.

The fact that the shear velocity (V_s) at the bottom is usually considerably less than the sound velocity in water inhibits the direct measurement of V_s by normal marine seismic survey techniques. This is the principal reason for the paucity of V_s data. Explosions near the bottom generate a large amount of compressional wave energy and

the most prominent arrivals containing shear energy are the Stoneley/Scholte waves. Vertically polarized shear, SV, is coupled to compressional, P, at each impedance boundary.

Horizontally polarized shear, SH, energy is decoupled from P in an isotropic system whose properties vary only with depth. Thus, an efficient source of SH energy recorded on horizontal geophones can provide relatively unambiguous information on V_s and S-wave attenuation as a function of depth in the bottom.

The possible effects of anisotropy and lateral heterogeneity on propagation loss are poorly known. Most marine sediments are expected to exhibit transverse isotropy, which is a form of anisotropy with a single, vertical axis of symmetry (Fryer and Miller, 1986). This can result from intrinsic anisotropy of gravitationally oriented particles, or pore spaces, or (more likely) from variations in sediment properties with depth at a scale small compared to a wavelength (Milholland *et al.*, 1980). Most observed (and imagined) situations produce higher compressional wave speed in the horizontal plane than in the vertical direction; horizontally propagating, horizontally polarized shear is faster than horizontally propagating, vertically polarized or vertically propagating shear. The observation of both horizontally polarized (SH) and vertically polarized (SV) shear along with compressional waves permits the estimation of the five independent elastic parameters of transverse isotropy (Berge *et al.*, 1989). "Shear wave splitting," i.e., different travel times between a given source and receiver of shear waves with orthogonal polarization, is a classical indication of seismic anistropy (Crampin, 1985).

Anisotropy without a vertical axis of symmetry and lateral heterogeneity can be caused by, e.g., azimuthal variations in sedimentation, lithification, and erosion. Obviously, complete characterization of the most general case is quite difficult. However, of the importance of these conditions on propagation can be estimated and predicted from the results of appropriate experiments in different environments.

The instrumentation, experimental procedures, and results from two, two-week cruises, in spring 1986 and 1988, off the southern coast of New Jersey and south of Martha's Vineyard are summarized in the following sections. Energy sources were developed to produce both longitudinally polarized energy (compressional, P; vertically polarized shear, SV; and interface waves, Rayleigh (LR), Stoneley/Scholte) and transversely polarized energy (horizontally polarized shear, SH; and Love waves, LQ). Three orthogonal components of motion and pressure are recorded, generally along linear profiles. Each of the 4 components produces unique data that provide additional information on wave type, velocity/attenuation structure, scattering, lateral heterogeneity, anisotropy, and instrument-bottom coupling (possible signal distortion). When possible, profiles along different azimuths are obtained to investigate azimuthal effects.

II. INSTRUMENTATION AND EXPERIMENTAL PROCEDURES

A. 1986 Cruise

The shear source sled developed for the 1986 cruise is shown in Figures 1A. It consists of two 10-cubic-inch airguns in heavy steel horizontal tubes mounted oppositely in a sled to fire either port or starboard from the direction of propagation to the receiver. The sled is coupled to the sea floor by its weight augmented by rails along its bottom. The superstucture is designed to flip the sled upright if it is tipped during deployment.

Figure 2 is a sketch of the field procedure: a toboggan bearing three orthogonal geophones and a hydrophone is deployed; the ship moves away, anchors and the shear sled is deployed and oriented; a seismo-acoustic record section is obtained by firing port and starboard shots at each distance as the toboggan is pulled toward the ship. If sea conditions are favorable, a "reverse profile" can be obtained by initially deploying toboggan and sled near each other and firing while pulling the sled away from the toboggan before shooting the normal sequence. P-SV mode energy is emphasized by adding port and starboard signals at each range; SH mode energy is emphasized by subtracting the two signals. Precise timing is obtained by firing the airguns electrically through the digital recording system. However, precise distances and orientations are more difficult to control and establish because of lateral motions of the ship. Misalignment of the horizontal components on the toboggan can be corrected (assuming negligible lateral refraction) by mathematically rotating the data to minimize the longitudinal signals on the transverse component; misorientation of the shear sled merely reduces the SH amplitudes.

B. 1988 Cruise

Experience from the 1986 cruise indicated that better resolution of the uppermost

sediment structure, where velocity gradients are generally greatest, requires higher frequency data and closer, more accurate distance spacing. This in turn, requires smaller source and receiver elements.

Shear sources developed for the 1988 cruise are sketched in Figure 1B. These three sources are much lighter and smaller than the original shear sled. Electrically fired shotgun shells containing various amounts of powder provide the energy. The upper two versions in Figure 1B are mounted on plates with runners to improve coupling to the sediment. The normal, coupling force is provided by the gun angle in version 1 and by sled weight in version 2. Version 3, which is lightest of the three, is cylindrical and coupling is provided by the two disks shown. As anticipated, these sources produced much higher frequency signals than the shear sled. However, the ratio of transverse to longitudinal energy produced was considerably less. Apparently, the greater bearing pressure of the shear sled coupled SH modes more efficiently. (The downward component of the shot in version 1 contributes to the P-SV radiation in addition to providing the desired large normal, coupling force.)

A completely new data acquisition system was designed and constructed during FY 88 for the 1988 cruise by Hawaii Institute of Geophysics to our specifications. The system consists of a streamer (ladder array) and shipboard recording equipment. The ladder array contains thirty nodes (seismic receiving points) at one meter spacing; each including three orthogonal accelerometers (flat from 2 to 500 Hz), a hydrophone and a vertical direction sensor (Figures 3 and 4, Harris and Sutton, 1988). The accelerometers can operate in any orientation: one accelerometer is in the streamer direction; the vertical direction sensor orients the two transverse accelerometers. The 120 accelerometer/hydrophone signals and 30 vertical direction signals are digitized at one of two digitizing units and transmitted via one kilometer of fiber optic cable to a PC type computer. The hardware and software required to receive the data and store it on

cassette tapes are also provided. The 16 bit A/D converters are capable of, e.g., digitizing all hydrophones at 2048 samples/sec and all accelerometers at 512 samples/sec Preamplifier gains can be adjusted in four groups along the array to compensate for spreading loss and attenuation. Good coupling to the bottom should be obtained since sensor symmetry has been maximized; coupling to the water has been minimized; and density is matched to the sediments. A smaller geophone array utilizing the same digital recording system was also used in the field work.

There are 10m extensions between the sensor nodes and the triangular housings at either end of the accelerometer array. The units containing port-starboard paired, shotgun-shell sources (Figure 1B) were mounted within the array in these extensions and fired through the array circuitry, providing precise time and distance control and reverse profile capability. Longer range data requires deploying sources beyond the array or between the array and the ship.

Because of the timing of funding and the ship schedule, there was no time for 'wet' testing the ladder array at Hawaii Institute of Geophysics or at Woods Hole Oceanographic Institution before the research cruise on R/V Oceanus. However, although we experienced considerable difficulty learning how to deploy the array we were able to obtain excellent data during three deployments and were able to reduce the total time for a multiple shot deployment to about three hours. During the third deployment four paired sources were used: at 1, 5, and 9 m from the nearest sensor node at the far end of the array and at 1 m at the near end to provide a reverse line.

III. EXPERIMENTAL RESULTS

A. 1986 Cruise

The radial-horizontal component record section shown in Figure 5 shows normally dispersed (i.e., lower frequencies have higher velocities) P-SV mode interface waves of the type used in most earlier experiments to determine sediment shear velocities. The dispersion results primarily from the effect of an increase in shear velocity with depth on the lower frequency, longer wavelength energy.

Figure 6 shows results of the combination of port-starboard shot pairs 27 and 28 at 135m distance using only the two horizontal components X and Y. When the source sled and geophone toboggan are oriented approximately correctly and the two sources and two receivers are well matched, $X_1 + X_2$ should be the longitudinal (radial) horizontal component of P/SV/LR/Stoneley-Scholte and $Y_1 - Y_2$ should be transverse horizontal, i.e., SH/LQ. In that situation $X_1 - X_2$ and $Y_1 + Y_2$ should be relatively small. A large signal on $X_1 - X_2$ or $Y_1 + Y_2$ indicates some violation of the assumptions concerning the instrumentation or different amounts of lateral refraction for longitudinal and transverse modes.

Times A and D indicate maxima on the $X_1 + X_2$ trace and are almost certainly longitudinal arrivals. The relatively large error-trace, $X_1 - X_2$, is about 90° out of phase with $X_1 + X_2$. Times B and C indicate maxima on the $Y_1 - Y_2$ trace. Time C represents a strong transverse arrival. B also probably is a transverse arrival since the error trace $Y_1 + Y_2$ at that time is small. The strong signal between C and D on error trace $Y_1 + Y_2$ looks like longitudinal motion arriving mostly in the Y (almost transverse) direction. This arrival is still a mystery. However, it is typical that summed transverse traces contain a significant amount of energy resulting from lateral refraction or some amount of asymmetric anisotropy. In some cases using an airgun suspended directly

above the bottom, which should have produced P/SV modes only, a great deal of transverse-horizontal motion is present, increasing with range.

It appears that conversion from longitudinal (P/SV) to transverse-horizontal (SH) motion provides a loss mechanism not generally considered in calculations of propagation loss (Carter *et al.*, 1987).

Full-waveform synthetic seismograms based on the "locked mode" technique developed by Harvey (1981) and the SAFARI code (Schmidt and Tango, 1986) are being used as an aid to improving the reliability and uniqueness of the velocity/attenuation models obtained from the data. In practice, velocity-depth sections based on core-log data and obtained using ray-trace methods by J. Ewing and others at WHOI were used as starting models that were then modified in attempts to improve the fit between data and synthetics.

The received signal is the convolution of the velocity/attenuation structure with the source and receiver characteristics. We believe we know and can correct for the receiver characteristics fairly well. We are able to model different source types, e.g., explosions in the water and dipole stresses or torques in the sediment in different combinations.

Figures 7 and 8 show some of the results of our modeling of the 1986 data. The velocity models illustrated here are appropriate for the AMCOR 6011 site off southern New Jersey. Figure 7 shows the shear velocity models (1 and 2, only) used for the synthetics illustrated in Figure 8. Model 1 is a simple homogeneous $V_s = 150$ m/s layer 10 m thick over a uniform half-space with $V_s = 300$ m/s. The layer thickness and velocities were estimated from available geological data. Model 2 is a layered approximation to J. Ewing's results from travel time analyses showing a positive gradient both in the silty-clay layer and in the underlying sand. Model 3 approximates the upper layer also with positive gradient but with lower average velocity than Model 2.

Figure 8A compares radial horizontal data and synthetics from Model 1 with $Q = \infty$. The qualitative match is quite good showing emergent arrivals near 300 and 150 m/s with comparable amplitudes. The transverse horizontal data and synthetics for Model 1 (not shown) do not seem to match as well. Although the prominent lower velocity arrivals agree with roughly average arrival times, the step-out of the data is significantly less (higher velocity) than the synthetics. Also, in contrast with the data, the synthetics grow somewhat with range. Model 2 appears to fit the transverse component data considerably better (Figure 8B).

The fact that different isotropic models give the best fit to the radial and transverse data suggests that the upper sediments are anisotropic (Sutton *et al.*, 1987). Berge *et al.*, 1989, indeed, have matched the data to a single anisotropic (transversely isotropic) model using our two isotropic models to obtain first estimates of the five anisotropic constants.

B. 1988 Cruise

In comparison with the 1986 data the 1988 data have much higher resolution both in wavelength (frequency) and in spatial sampling. Also distances are better determined, both from higher sampling rate on the hydrophones and from the sources being fixed in the arrays with respect to the receiving nodes. The source sleds were attached to both the geophone string and the ladder-array at various distances with respect to the nearest sensor.

Some results from the ladder array deployment south of Martha's Vineyard are shown in Figures 9 through 14 (Sutton *et al.*, 1989). Radial and transverse-horizontal record sections are shown in Figure 9. The rapid change in both phase and group velocities observed within the first few meters contains information about the uppermost sediments that would be lost or ambiguously interpreted from data with coarser spacing.

Four velocity-attenuation models for the Martha's Vineyard profiles are shown in Figure 10. In these models we are mainly trying to match the later parts of the wave train of the transverse-horizontal component data. Model 1 approximates a linear velocity gradient; model 2 has a more realistic gradient decreasing with depth; models 3 and 4 have a low-velocity layer, less than one-meter thick at the top. In all models Q (amplitude attenuation is proportional to exp $[-\pi fr/Qv]$) is finite; only Q (model 4) is shown in the figure.

The transverse-horizontal component seismogram sections for the four models are shown in Figure 11. All phase velocities less than 500 m/sec are included in these synthetics. In comparing models 1 and 2, it is interesting to note that the higher velocity model 2 produces the lower prominent group velocities; the high near-surface gradient traps much of the energy. Compared to the data, model 1 is too fast and model 2 is too slow. Models 3 and 4 provide better matches to the data; model 4 shows a somewhat better fit to the transverse data. In Figure 12, model 4 synthetics for both radial and transverse horizontal components are compared. Both phase and group velocities match quite well, but the signal durations could be better matched. The radial synthetics and the transverse data have the longer wavetrains. Figure 13 is a comparison between the model 4 transverse synthetics and the transverse data obtained from a shot at the opposite end of the ladder array during the same deployment as the data in Figures 9 and 12. The wave trains are shorter and the match with synthetics is excellent. The differences in data character must result from some movement of the array between shots and/or different source coupling to the bottom.

In Figure 14, the Martha's Vineyard array data are expanded and amplified. Prominent phase velocities, indicated by sloping lines range from 22 to 250 m/sec. Also shown in Figure 14 are p-τ plots obtained directly from the data by slant-stacking the time-distance record sections. The slownesses shown range from 0.5 to 25 sec/km, i.e.,

phase velocities from 2000 to 40 m/sec. The p-τ (slowness-intercept) plots display the first step in analytic (objective) methods to obtain phase velocity dispersion curves (McMechan and Yedlin, 1981) or velocity vs. depth sections (Clayton and McMechan, 1981).

The guided wave phase velocity inversion method of McMechan and Yedlin involves the direct transformation of the p-τ data into p-ω (or phase velocity, 1/p, vs. frequency) plots. This procedure should automatically separate and display dispersed energy from the fundamental and successive higher modes in well sampled situations.

The "diving wave" velocity-depth inversion method of Clayton and McMechan involves analytically distorting the τ coordinate of the p-τ plot into the depth coordinate. As for the phase velocity inversion method, the technique requires a good, fairly dense starting record section. Methods are available for interpolating missing or poor records to improve the quality of the inversion.

The "diving wave" and guided wave inversion procedures discussed above are much faster computationally than the generation of full-waveform synthetic seismograms and can be used to produce preliminary models. In addition, synthetic seismograms can be inverted by these same procedures and be compared with data in the p-τ, p-ω, or p-depth domains where it can be easier to resolve remaining differences and/or estimate uncertainties between the model(s) and the actual velocity/attenuation vs. depth relationship.

IV. CONCLUSIONS

It has been demonstrated that high resolution longitudinal and transverse mode shear data can be obtained in shallow water regions and inverted to obtain shear velocity/attenuation vs. depth models.

Each of the 4 components, 3-motion plus pressure, produces unique data that provide additional information on wave type, velocity/attenuation structure, scattering, lateral heterogeneity, anisotropy, and instrument-bottom coupling (possible signal distortion). Anisotropy and lateral heterogeneity can have important effects and contribute to propagation loss. Shear data is more difficult to obtain than compressional and horizontally polarized shear is more difficult to obtain than vertically polarized shear. However, the extra effort provides information on anisotropy and lateral refraction not available from pressure or vertical motion data.

There is still much room for improvement in the instrumentation and field techniques. The steep gradients and short wavelengths of shear waves in the low-velocity, uppermost sediments requires small sensor dimensions and close sensor spacing for reliable results. Small, efficient SH sources need improvement. Array handling in wind, sea, and current can be difficult; the orientation of a shot line generally depends upon these factors rather than the bottom conditions being studied.

V. ACKNOWLEDGEMENT

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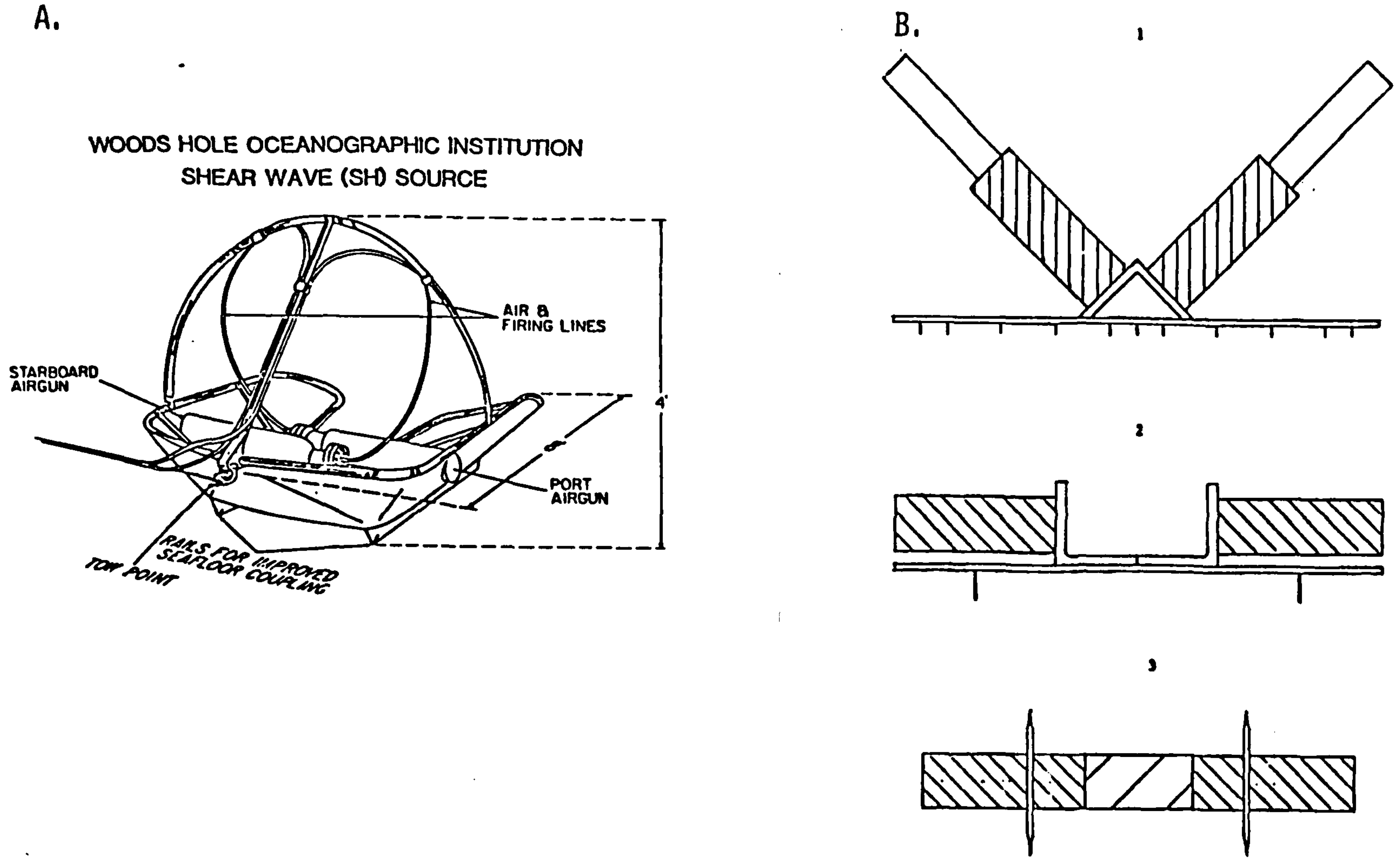

Figure 1. Horizontal shear wave sources: A. airgun shear sled; B. three versions of shotgun shear sources.

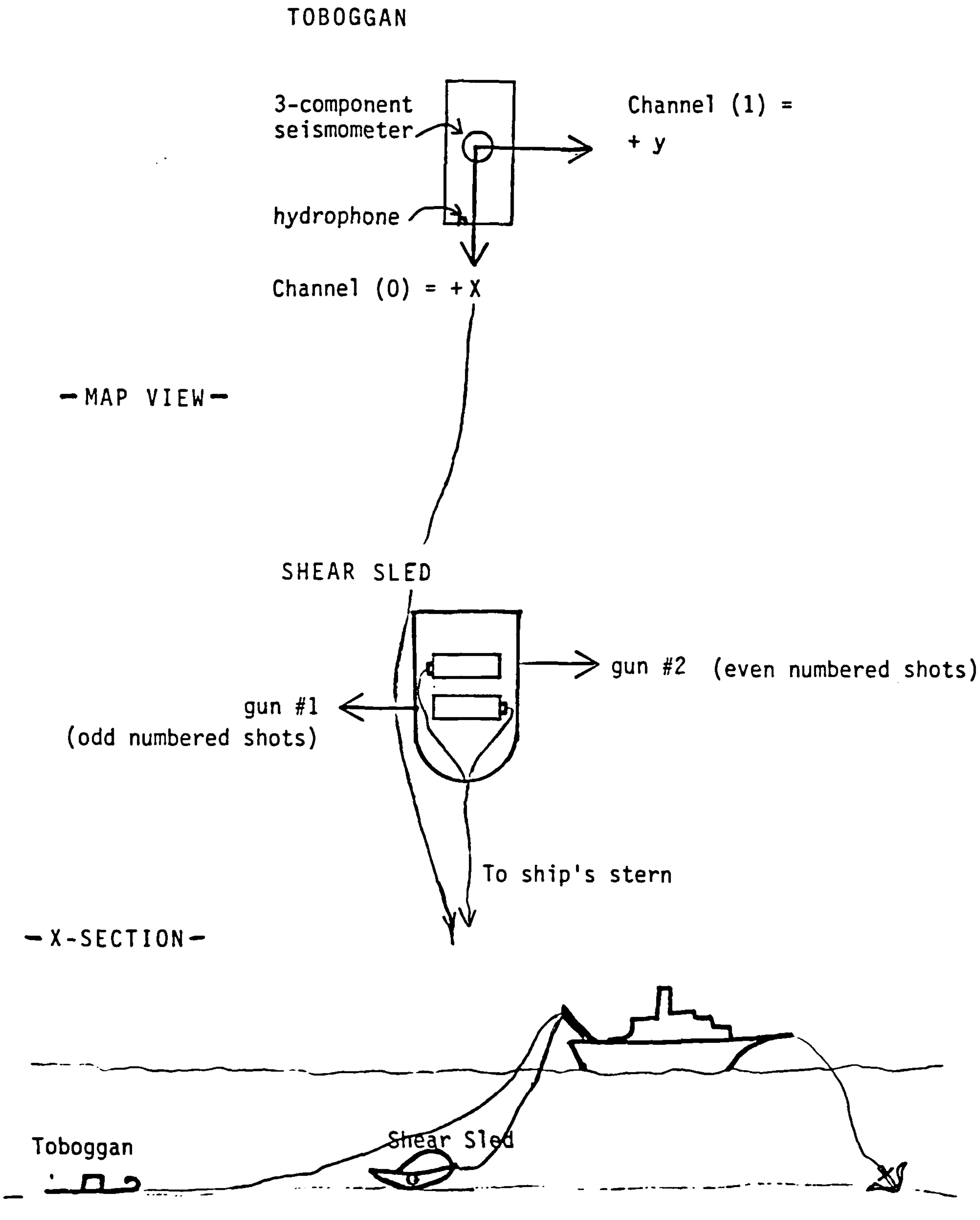

Figure 2. **Schematic sketch of deployment scheme and orientation of SH shear-generator sled and 3-component geophone-hydrophone toboggan. In addition to the labelled horizontal components, the toboggan contains a vertical seismometer and a hydrophone. Note the ground moves opposite the direction of the expelled air, shown by the arrows.**

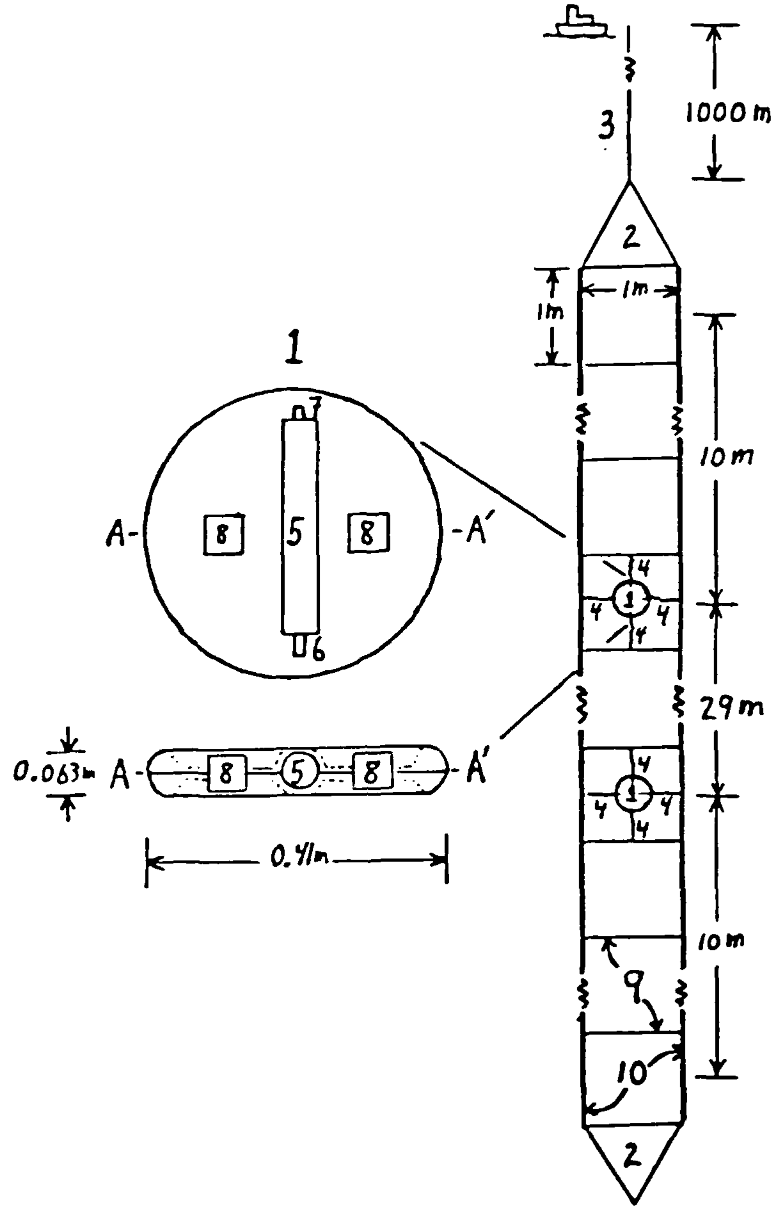

Figure 9. Thirty node digital accelerometer/hydrophone (ladder) array: 1. sensor puck, fiberglass covered, resembling four quadrant waffle; 2. end triangle housing A/D and electro-optical converters; 3. armored electro-optical cable; 4. loose chain coupling puck to array; 5. three-component accelerometer pressure case; 6. hydrophone; 7. electrical connector; 8. balance weight; 9. rigid cross-members; and 10. flexible electrical and strain cables in split fire hose.

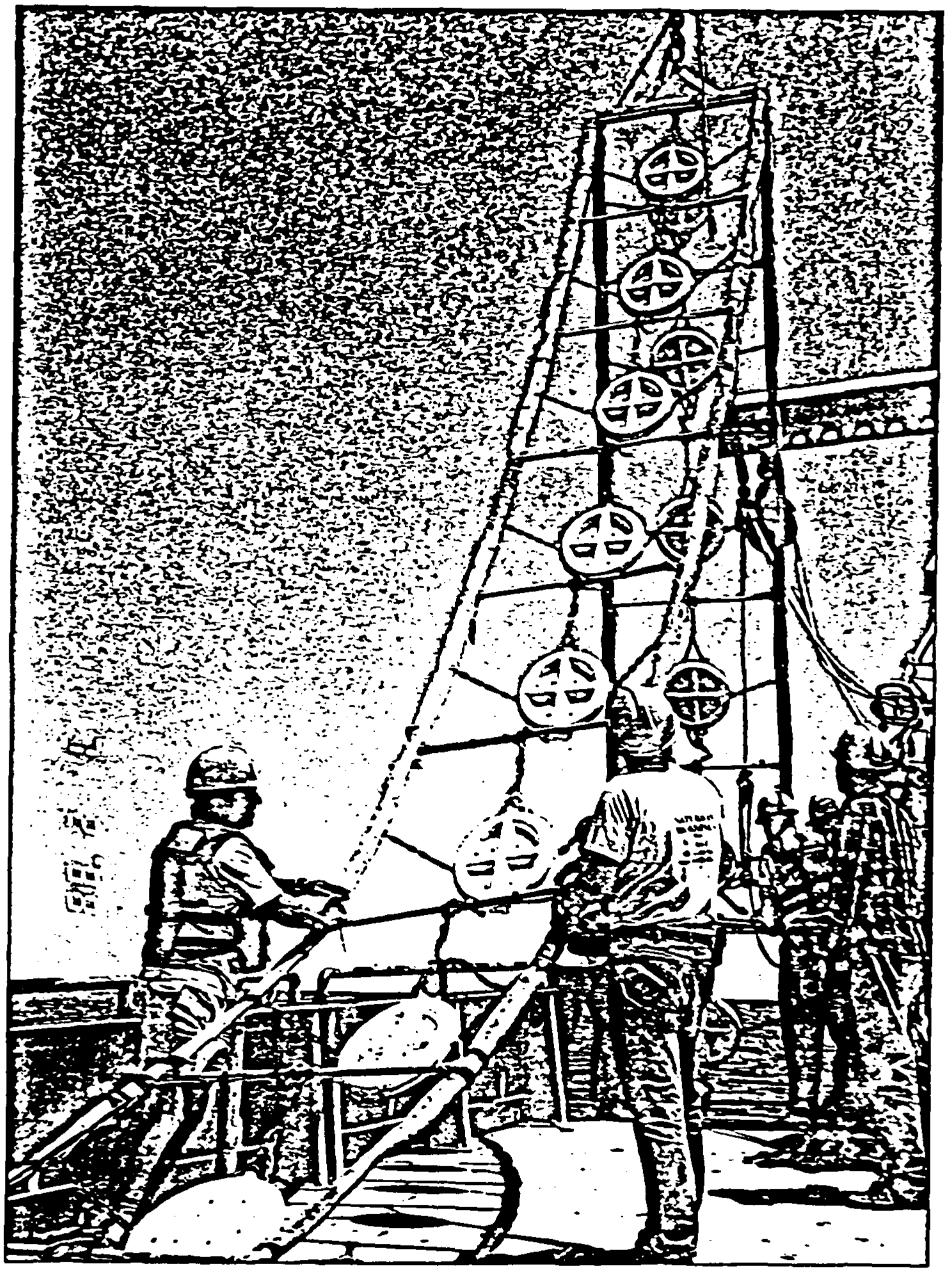

Figure 4. Deploying multi-sensor ladder array from deck of R/V Oceanus.

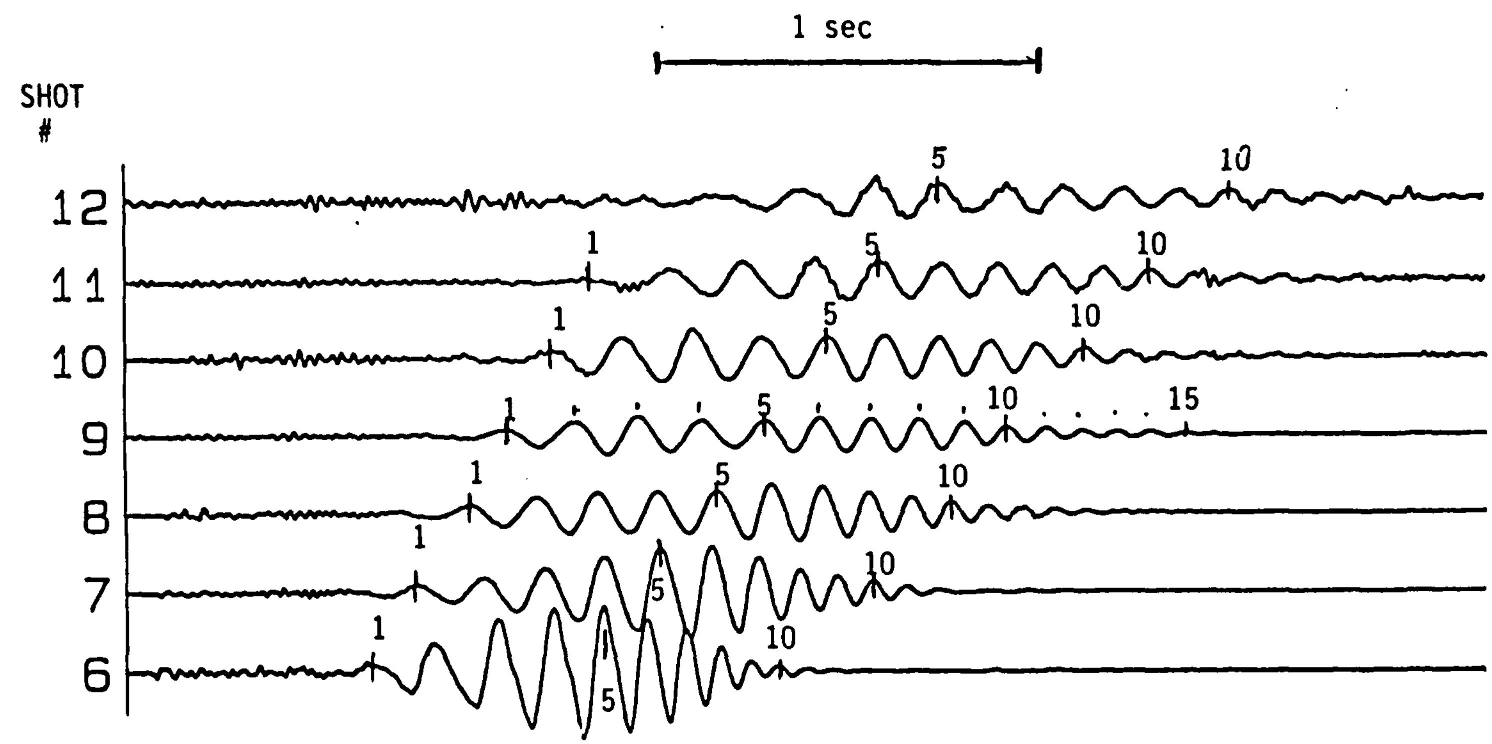

Figure 5. Normally dispersed Rayleigh (LR)/Stoneley-Scholte type waves recorded on (mostly longitudinal) x-component horizontal geophone. Depth = 8.6 m. Profile 10 Jn 1255 (Run 3) in Delaware Bay. Maximum range shown is 225 m. Note lengthening of wavetrain and, therefore, increasing periods of cycles, between peaks 1 and 10 with increasing range. The lowest and highest observed group velocities are about 50 and 160 m/sec near 11 and 5.5 Hz, respectively.

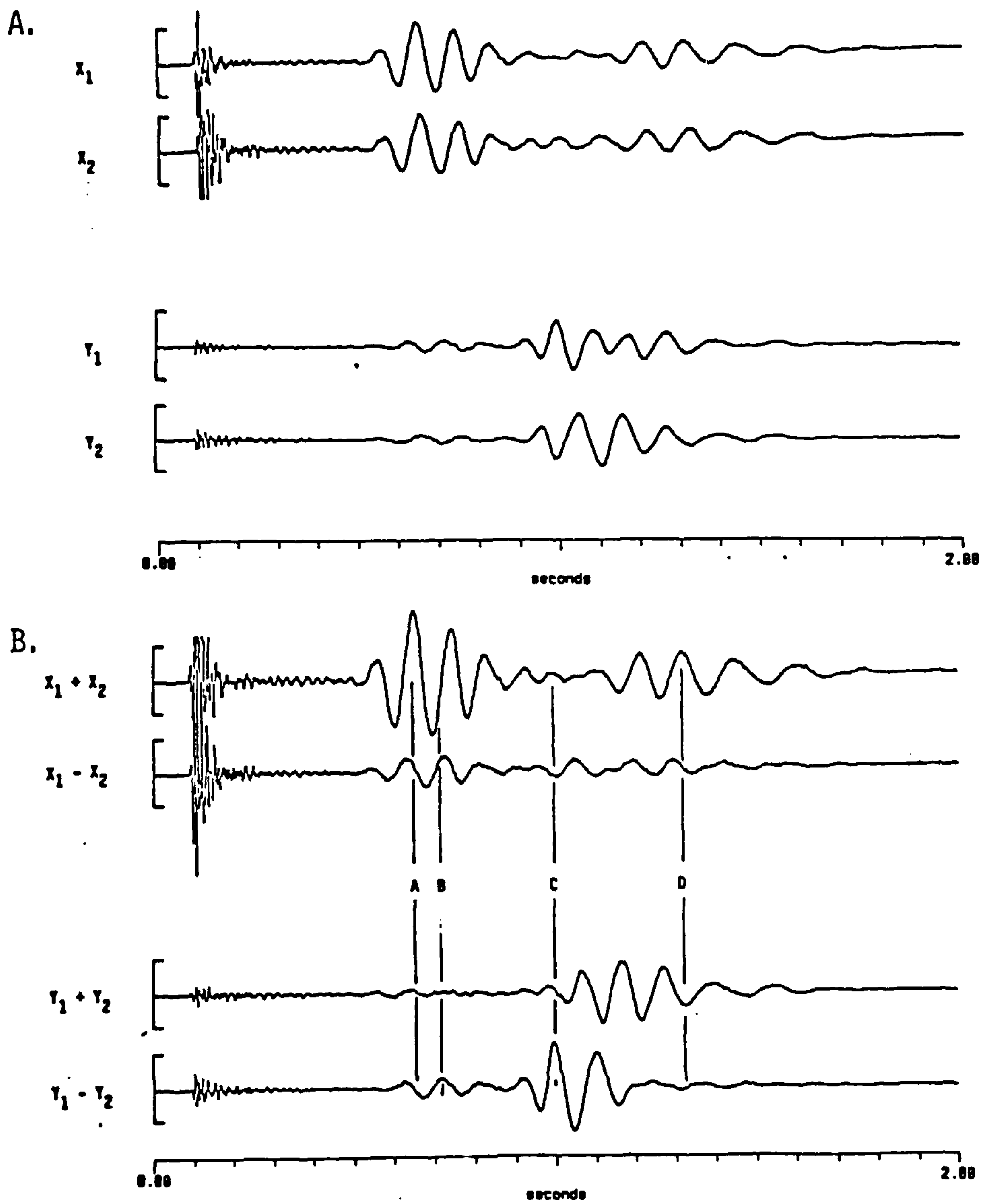

Figure 6. Profile 18 Jn 1925 shots 27 and 28 alternate pair at 135 m distance. A. Mostly longitudinal x-components and mostly transverse y-components show quite different signals. x shows large, high-frequency early "water wave" arrival and in-phase later arrivals, y shows small, high-frequency early "water wave" arrival and much out-of-phase later signal.

B. Sum and difference records for both the x and y records shown in A. $x_1 + x_2$ should be mostly longitudinal (P/SV/LR) energy. $y_1 - y_2$ should be mostly transverse (SH/LQ) energy. The other two traces, $x_1 - x_2$ and $y_1 + y_2$ should be small. Lines A, D, and B, C indicate times of maxima of longitudinal and transverse energy, respectively.

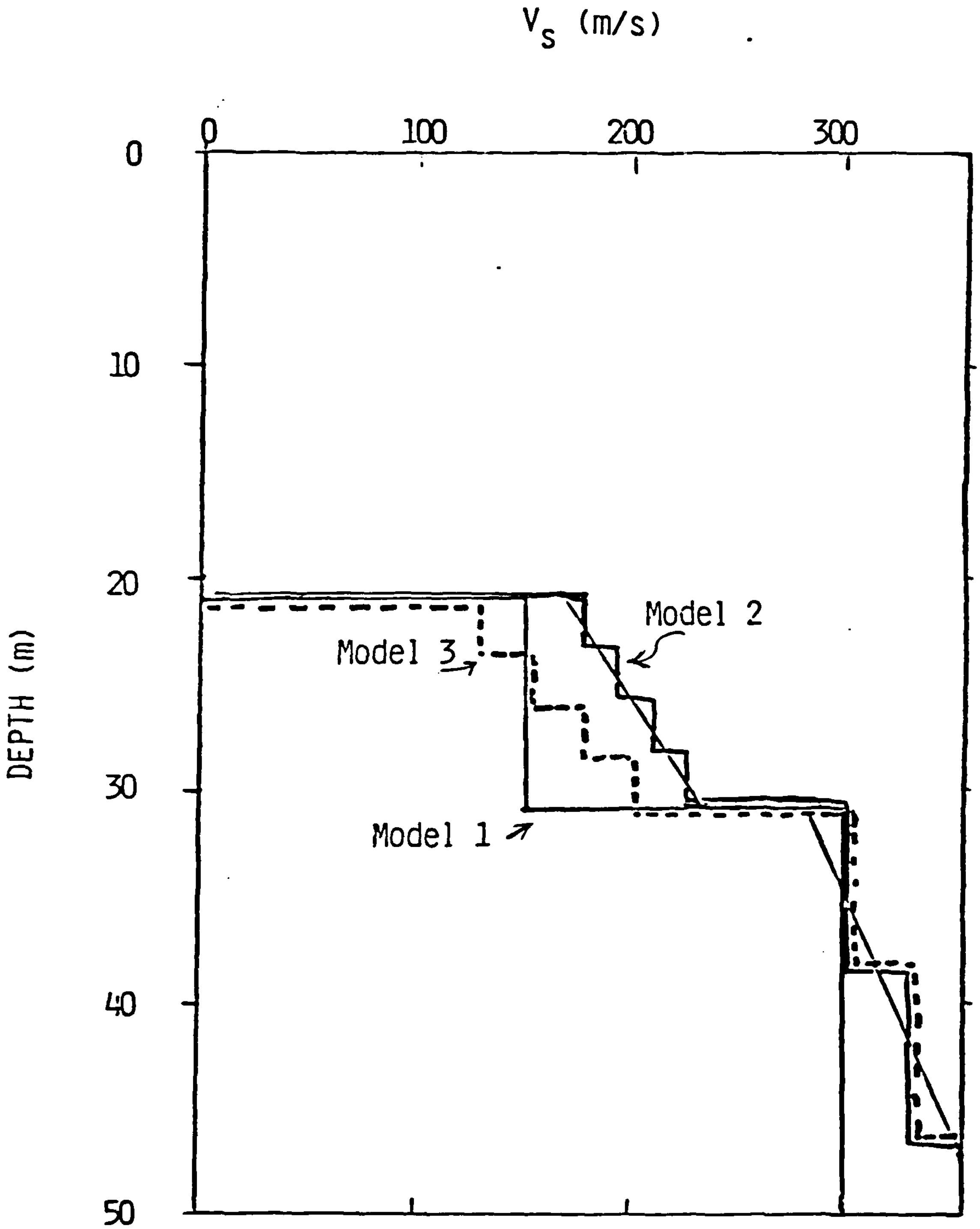

Figure 7. **Shear wave velocity models appropriate for the AMCOR 6011 site (off southern New Jersey), used in the synthetic record sections shown in Figure 8. Model 1 is a simple 10 m layer over a higher velocity half-space; Model 2 matches the results from travel-time analysis (light sloping lines); Model 3 has an average velocity in the upper portion close to Model 1. Compressional velocities in the sediments increase from 1610 to 1720 through the section.**

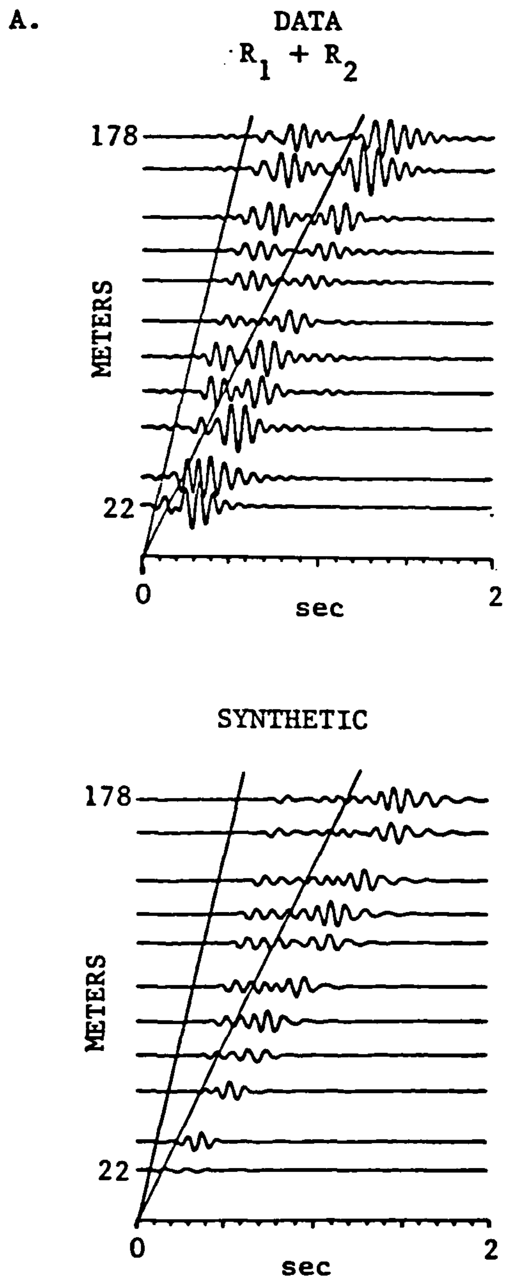

Figure 8. Data and synthetics for AMCOR 6011 site, 2-15 Hz band-pass, reference velocity lines are 150 and 300 m/sec: A. radial horizontal ($R_1 + R_2$) data and Model 1 synthetics ($Q = \infty$); B. transverse horizontal ($T_1 - T_2$) and model 2 synthetics ($Q_\beta = 30$ in upper 10m). Trace amplitudes in this and all following record sections are increased proportional to distance.

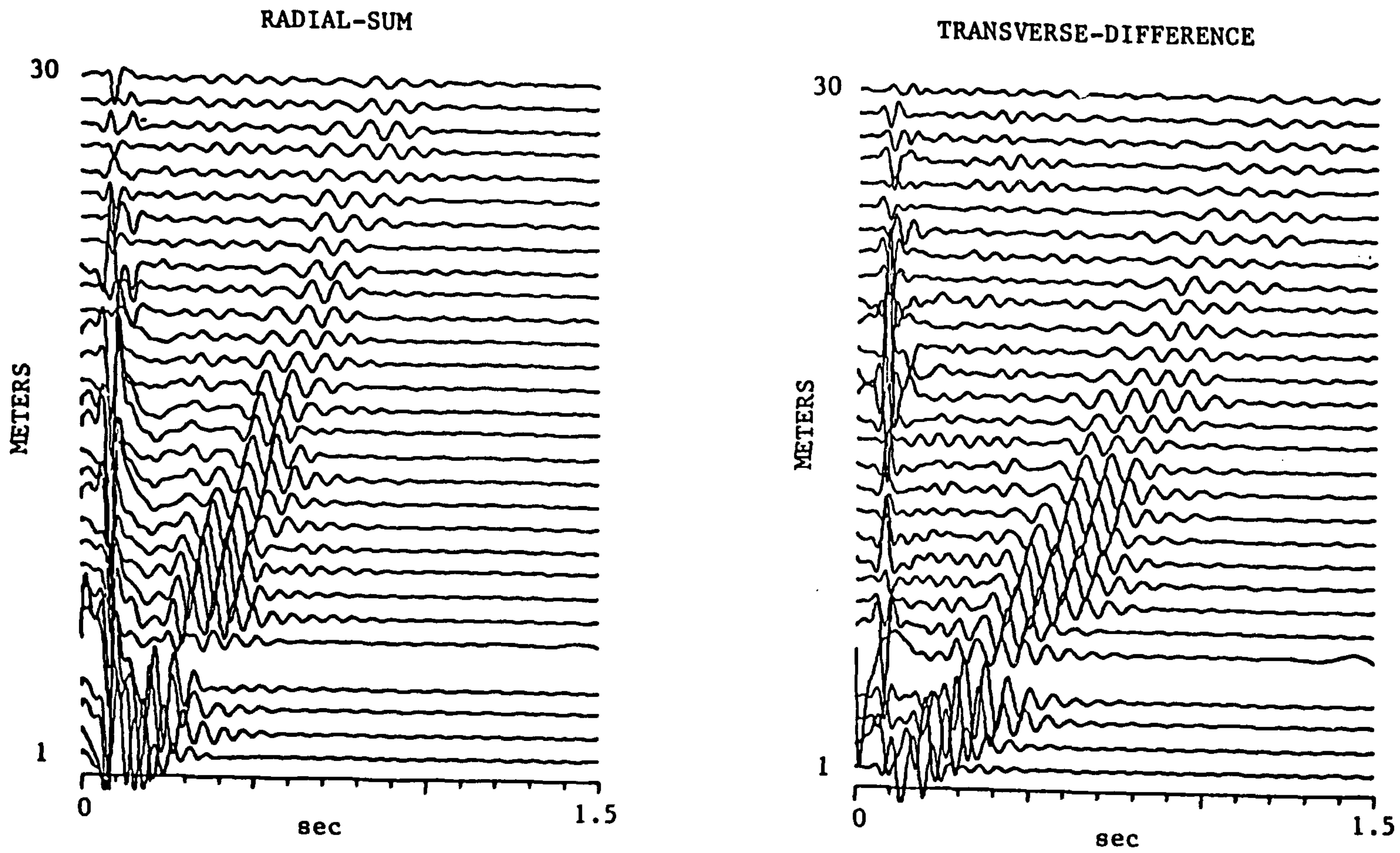

Figure 9. Horizontal component data from ladder array south of Martha's Vineyard. The receiving node at 5 m was defective. Note especially the rapid change at close ranges.

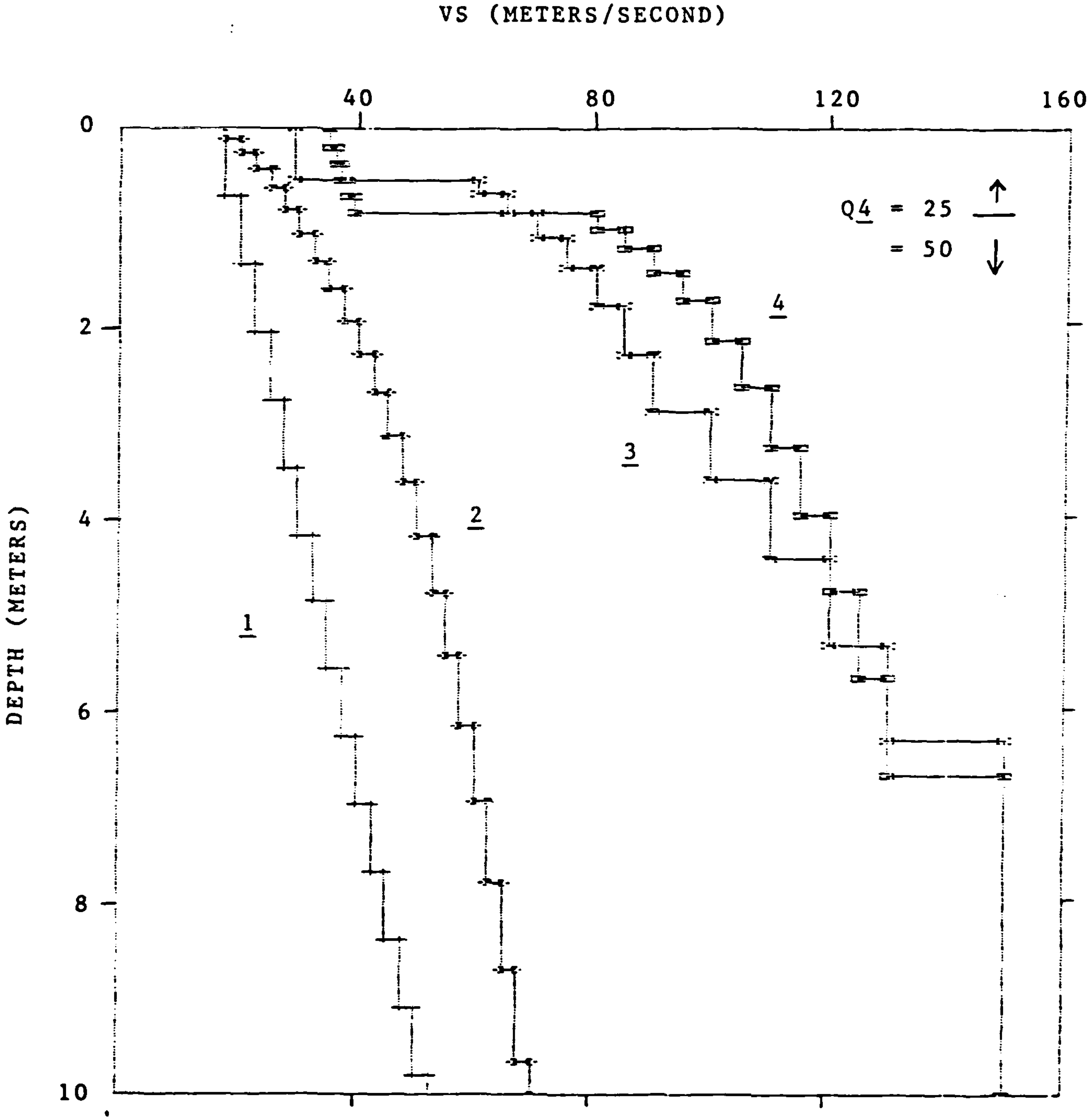

Figure 10. **Shear wave velocity/attenuation models for Martha's Vineyard data.**

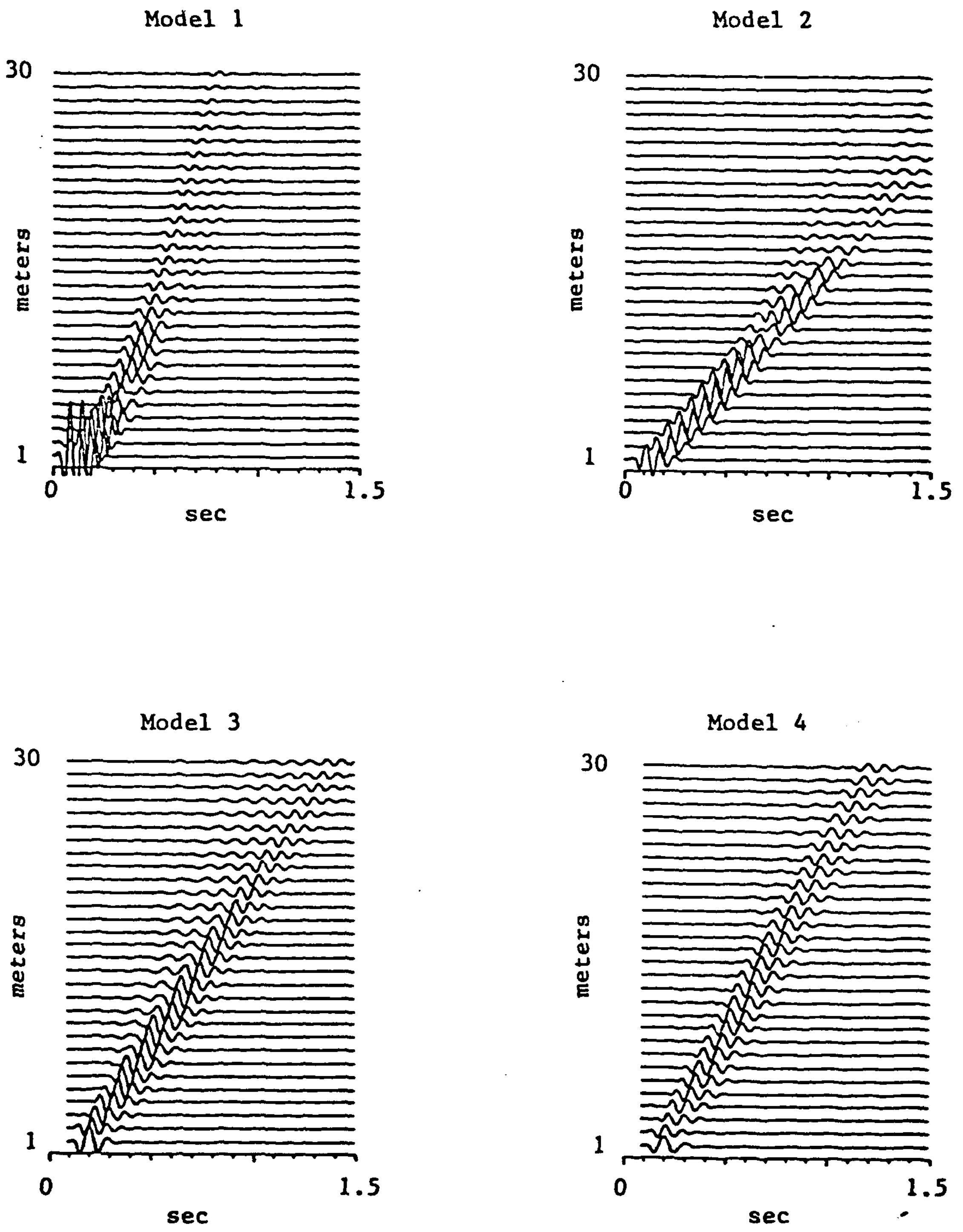

Figure 11. **Transverse horizontal component synthetics for Martha's Vineyard models of Figure 10.**

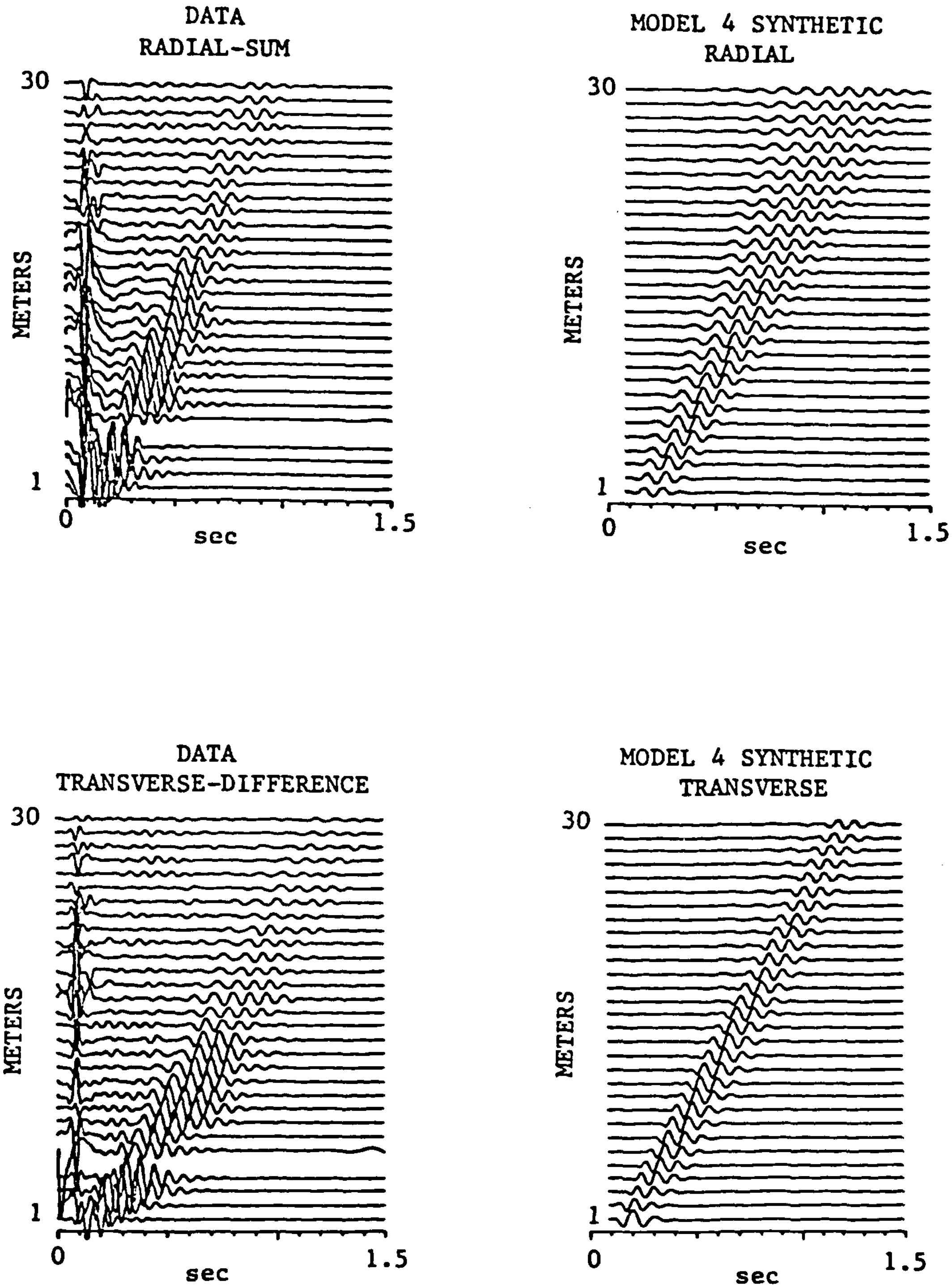

Figure 12. Comparison of ladder array data from Martha's Vineyard with model 4 synthetics.

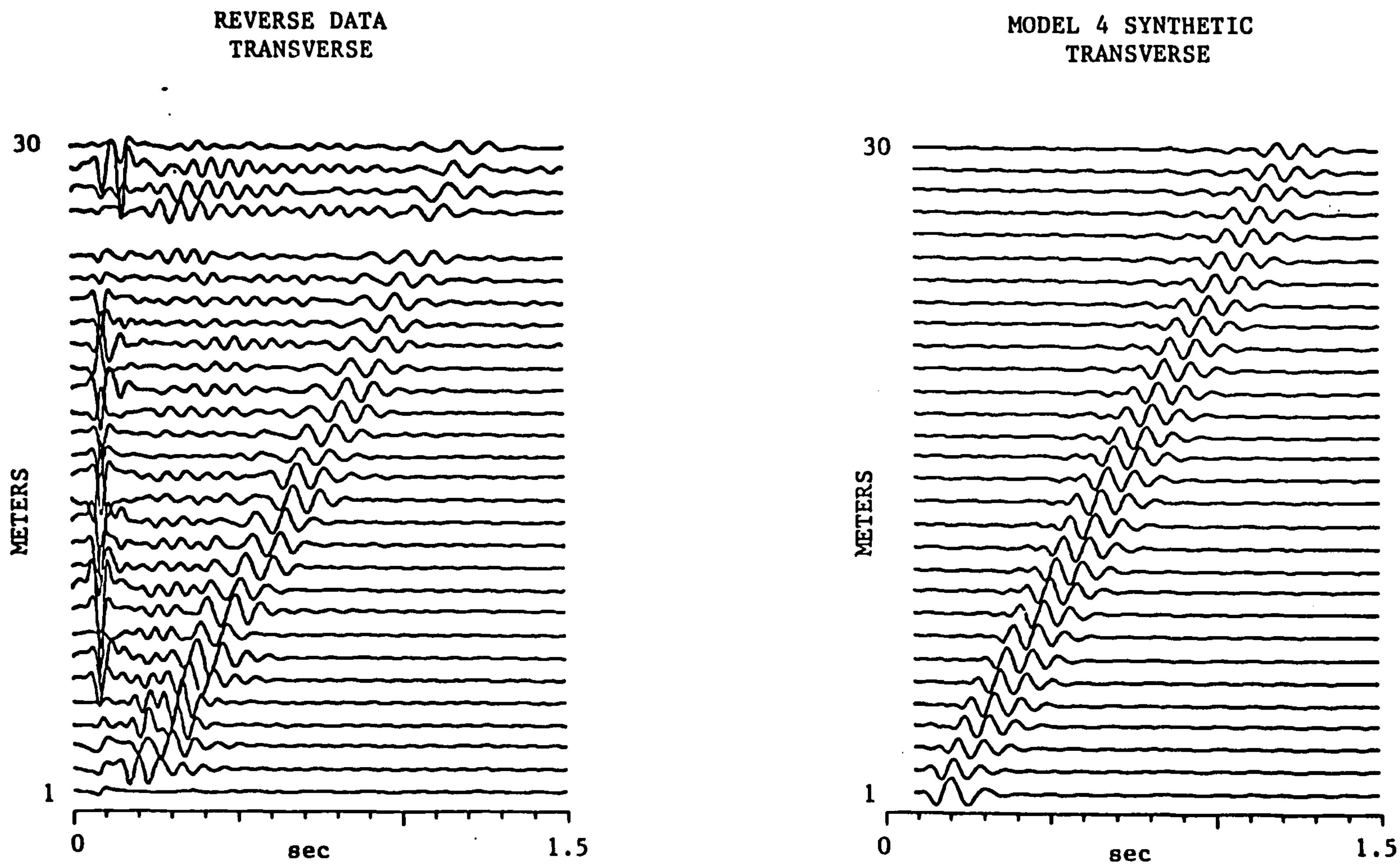

Figure 13. **Comparison of transverse horizontal data from propagation direction reverse to that of Figures 9 and 12 with model 4 synthetics.**

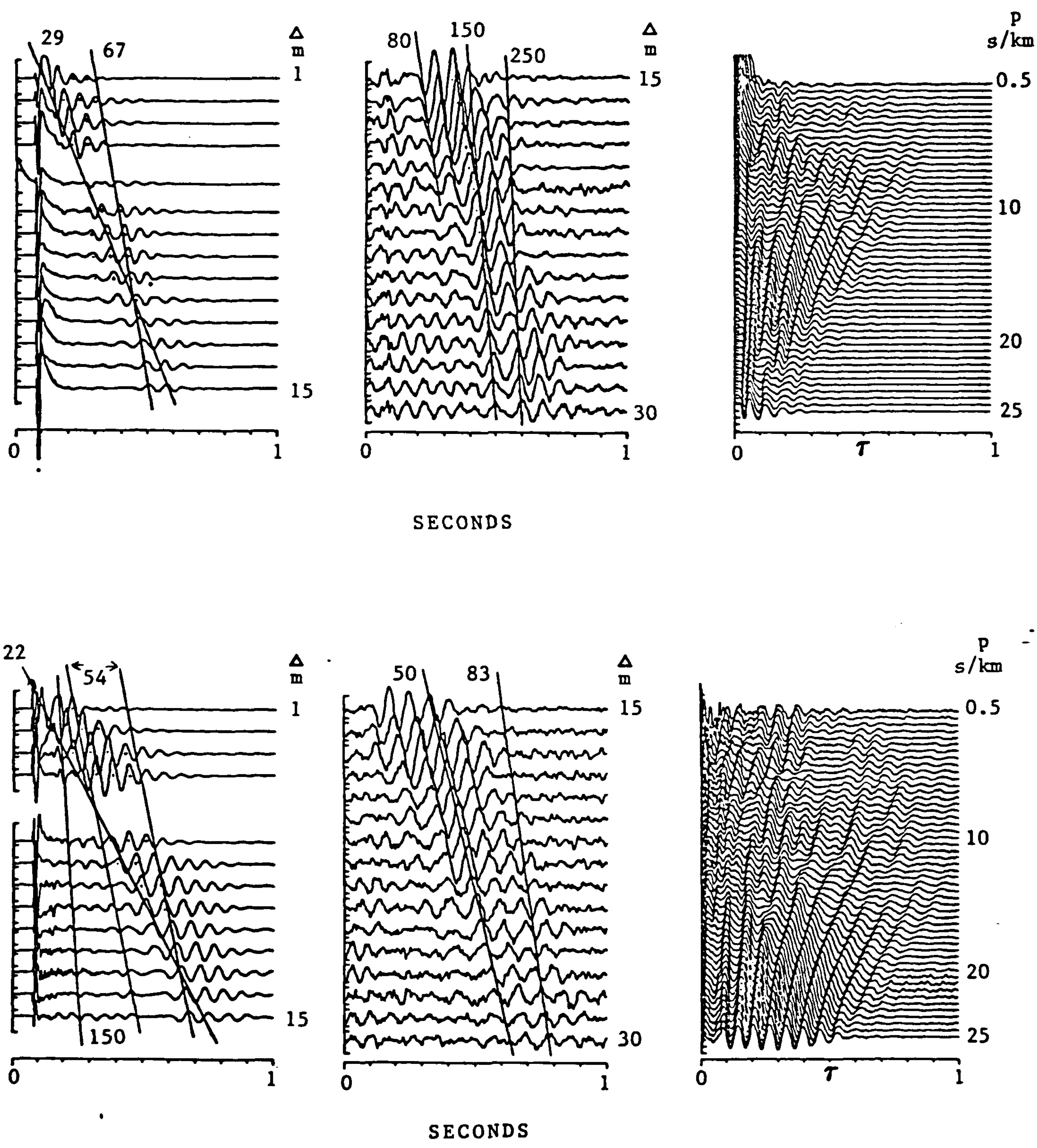

Figure 14. Expanded and amplified ladder array data from south of Martha's Vineyard and slowness-intercept (p-τ) plots obtained by direct inversion: top, radial-sum; bottom, transverse difference. Phase velocity slopes are m/sec. Note the 15-30 meter records are offset 0.5 sec.

Appendix B
(Submitted to Geophysical Journal International)

In Situ measurement of transverse isotropy in shallow–water marine sediments

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SUMMARY

The interleaving of parallel isotropic lamellae of contrasting mineralogical composition makes almost all marine sediments anisotropic, the form of anisotropy being transverse isotropy with a vertical axis of symmetry. Yet conventional marine seismic experiments cannot quantify the anisotropy because they do not record unconverted shear waves. In 1986, Rondout Associates, Inc. (RAI) and Woods Hole Oceanographic Institution (WHOI) recorded direct shear waves in anisotropic shallow marine sediments by using a newly developed ocean-bottom shear source and a multi-component on-bottom receiver. The seismic experiment was conducted in 21-m-deep water about 10 km east of the New Jersey coast. In this paper, we describe the anisotropy in the top 50 m of marine sediments beneath two of the RAI/WHOI refraction profiles. We use an anisotropic reflectivity program to produce synthetic seismograms to estimate the five independent elastic stiffnesses necessary for describing the transverse isotropy. Our synthetics fit the vertical and two horizontal components of the data for both profiles. The two intersecting refraction profiles are 150 m and 200 m long. These profiles are not long enough to constrain compressional wave velocities and anisotropy, but are quite adequate to find the shear wave anisotropy. A nearby drill hole showed that the sediments are interbedded silty clays, clays, and sands. The data require low shear velocities (< 400 m/s) and low Q_s (< 100) in about the top 30 m of the sediments. In the top 10 m of the sediments, silty clay exhibits $\sim$ 12–15 % anisotropy for shear waves.

Key words: seismic anisotropy, transverse isotropy, marine sediments, shear waves.

Appendix C

(To be submitted to Journal of Geophysical Research)

Shallow Water Sediment Properties Derived from High Frequency Shear and Interface Waves

Jerry A. Carter, John I. Ewing, George H. Sutton, and Noël Barstow

Abstract

Low frequency sound propagation in shallow water environments is not restricted to the water column, but must involve the sub-bottom. Thus, knowledge of sub-bottom velocity/attenuation structure is essential input for predictive propagation models. To estimate these important properties, we use bottom mounted sources and receivers to make measurements of shear and compressional wave propagation in shallow water sediments of the continental shelf. Experiments were conducted offshore New Jersey during the summers of 1986, 1988 and just south of Martha's Vineyard during the summer of 1988. For the most part, the measurements were made in areas where boreholes and high-resolution reflection profiles give substantial supporting geologic information about the subsurface. This provides an opportunity to compare results of physical properties of the seabed determined from inversion of seismic data with the "ground truth" properties. Sources were designed with the primary purpose of generating SH waves, but they also produced SV and P waves. Four-component data were obtained from receiving packages containing three orthogonal geophones and a hydrophone. Each of the components recorded produces unique data that provide additional information on wave type, velocity/attenuation structure, scattering, lateral heterogeneity, and anisotropy. The 1986 measurements were made with source detector offsets up to 200 m producing P and S wave velocity vs depth profiles of the upper 30 to 50 m of the seabed. The 1988 measurements were made with smaller source devices designed to emphasize higher frequencies and recorded using a short (30 m) sensor array with 1 m element spacing. These measurements focused on recording shallow structures at high resolution. The data are inverted for velocity/attenuation as a function of depth with the aid of synthetic seismograms and other analytical techniques. Results give strong evidence of anisotropy and lateral heterogeneity in shear velocity of the uppermost sediments at a number of locations.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Research conducted under this contract was part of the Shallow Water Acoustics ARI. The long-range scientific objectives of the ARI were to determine the physical parameters that control acoustic propagation in shallow water and their relationship to geological structure and processes in order to improve acoustic monitoring capability. Specific objectives of this contract were to develop instrumentation, field procedures, and data inversion methods required for efficient high resolution determination of elastic parameters of bottom sediments as functions of depth and location, and to evaluate effects of lateral heterogeneity and anisotropy. This research was conducted in close cooperation with John I. Ewing and others at Woods Hole Oceanographic Institution. This research has demonstrated that high resolution longitudinal and transverse mode shear data can be obtained in shallow water regions and inverted to obtain shear velocity/attenuation vs. depth models.

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